ACCURACY TESTS FOR SONIC TELEMETRY STUDIES IN AN ESTUARINE ENVIRONMENT

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Abstract: We evaluated accuracy and precision of a directional sonic telemetry system and 2 positioning systems to study sea turtle (Cheloniidae) use of estuarine habitat in Core Sound, North Carolina. Accuracy and precision of location estimates affect the power of statistical tests for use of habitat studies and define the amount of movement that can be reliably measured. Angle errors associated with the sonic system averaged −2.5° ± 5.67 (SD) for a 95% error arc of ±11.34° (range −17–12°). We obtained 45 location estimates after correcting 90 bearings for bias. Location errors (E), obtained from stationary positions at 400–1,200 m, ranged from 14.6 to 281.0 m with a median of 75.6 m. The 90 and 95% confidence areas for these data were 11.1 and 21.2 ha, respectively. Location error varied ($P < 0.01$) with geometric mean distance (D_g) between receivers and transmitters. Areal measures of confidence obtained at the D_g 500–600 m were the smallest (2.1–2.8 ha) among 3 distance intervals within 500–1,200 m. Attained levels of accuracy and precision were adequate to determine turtle movement and distribution in relation to selected fisheries activities, but of limited value for use of habitat studies. Inaccurate position estimates of monitoring platforms (e.g., boats) also affect location estimates. Precision of position estimates of a stationary boat anchored at a known location (i.e., channel marker) were poor, averaging 62 m, when obtained from Long Range Navigation System (LORAN). In contrast, positions obtained from Differential Global Positioning System (DGPS) varied by 3 m. The DGPS did not affect ($P = 0.94$) location estimation. Average difference between estimates using known location coordinates and those obtained from DGPS was 0.56 with a 95% confidence interval of ±1.29 m. We recommend that DGPS be used when evaluating sea turtle use of habitat. The DGPS was more accurate than LORAN and was unaffected by geography.

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Estuaries are valuable habitats to sea turtles (Ehrhart 1983, Lutcavage and Musick 1985, Keinath et al. 1987, Dodd 1988), especially for immature turtles (Crouse et al. 1987, Natl. Res. Counc. 1990). Surveys conducted since 1988 have underscored the importance of North Carolina's inshore waters, particularly the Pamlico-Albemarle estuarine complex, to juvenile loggerheads (*Caretta caretta*), Kemp's ridley (*Lepidochelys kempi*), and green (*Chelonia mydas*) sea turtles (Epperly et al. 1995). However, few data exist on their spatiotemporal distribution and use of habitat (e.g., foraging). Sea turtle use of habitat and movement studies have relied on radio telemetry (Odgen et al. 1983, Byles 1988). Main advantages of this technology have been that its range enables the search of relatively large areas (Winter 1983) and techniques to assess accuracy and precision are well developed (White and Garrott 1990). However, radio telemetry has a number of limitations when used for sea turtle studies. First, detection of instrumented animals needs to be made during a relatively short surfacing time window (e.g., <120 sec; Byles 1988). Signal attenuation in salt water (Winter 1983), coupled with constraints on time available to detect surfacing turtles, may preclude accurate location estimates. Second, it is assumed that the turtle, as it surfaces, does not travel outside the used habitat. Descriptions of surfacing events of Kemp's ridley and loggerhead turtles suggest that this assumption is violated frequently (Byles 1988).

Sonic telemetry enables uninterrupted tracking and accumulation of position data, but its usefulness hinges on achieving acceptable levels of accuracy and precision. Accuracy tests have been conducted for sonar buoy arrays (Hawkins et al. 1980, Armstrong et al. 1988, Lagardere et al. 1990). The reported level of accuracy for this system between known and estimated locations is ≤1 m. Once the animal moves outside the sonar buoy array, however, directional hydrophones must be used to determine position (Clark and Green 1989). Directional sonic telemetry has been used to study movements and feeding ecology of sea turtles (Mendonça 1983, Byles 1988), but system accuracy and precision were not reported. We report on accuracy and precision obtained during tests of a commonly used directional sonic telemetry system in channel habitats in Core Sound, North Carolina. We compared areal measures of specified statistical confidence with the size distribution of habitat polygons in southern Core Sound, and evaluated the appropriateness of the system for use of habitat studies (Nams 1989, White and Garrott 1990). We also report on the accuracy of LORAN and DGPS to determine the location of receiving stations. Both systems are used to determine boat location from which instrumented turtles are triangulated.

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METHODS

We conducted the study in Core Sound, North Carolina, a 24,000-ha, shallow ($\bar{x}$ = 1 m), polyhaline body of water in the southern portion of the Pamlico-Albemarle estuarine complex (Roelofs and Bumpus 1953). Habitats within Core Sound included shallow muddy creeks, bays with limited seagrass beds along the western shore, channels (<3-m water depth) in the open sound, and a broad, shallow shelf to the east that contained expanses of seagrass behind the barrier islands (Ferguson et al. 1993).

The NCGS surveyed 13 channel markers and beacons, located from Harkers Island to Marshallberg (Fig. 1). These served as transmitting-receiving stations. We obtained the North American Datum (NAD83) geographic location (metric), bearings, and distance between markers and beacons from the NCGS. We conducted accuracy tests using sonic transmitters (approx 75 kHz, model CHP-85, max. range 3 km) and a Sonotronic hydrophone (model DH-2) and digital receiver (model USR-5). We mounted the hydrophone and compass on a 1.2-m-long PVC pipe and aligned them visually by running a cord from the center of the hydrophone to the compass notch (indicating bearing direction) and squaring off the flat face of the hydrophone with the squared edge of the compass. We attached transmitters to channel markers and beacons at mid-depth (approx 1.5 m). We used 30 bearings/transmitting-receiving station for angle error evaluation.

We obtained 15 pairs of additional bearings from each of several pairs of receiving stations to estimate point locations. We used the "loudest signal" technique (Springer 1979:928), recording bearings to the nearest degree in reference to magnetic north. Two observers collected test data during 2 weeks in June 1991. To maximize bearing independence and reduce observer bias, true bearings were unknown to observers, selection of the loudest signal was made by 1 observer unaware of the compass and hydrophone handled by the second observer, and hydrophones were removed from the water between readings.

We evaluated angle errors to determine system bias, observer precision, and to correct for bias, if necessary, before estimating point locations (Springer 1979, Lee et al. 1985, White and Garrott 1990). Angle error is reported as mean angle error ($\bar{e}$) ± SD. We used t-tests to determine if the distribution of angle errors differed from zero and if precision between observers was different. We tested for differences in angle error among transmitting-receiving stations using a random effects analysis of variance (ANOVA). Angle error data met assumptions of normality.

We estimated locations with Lenth's maximum likelihood estimator (White and Garrott 1984). We adopted the location error method to report our measures of accuracy and precision (Zimmerman 1992). Estimated location accuracy is the median location error (E_m), the median of linear distances between known and estimated locations. Distribution of location errors (E) was nonnormal (Shapiro-Wilk W = 0.94, P = 0.03). Normality was not expected because error distances were $\geq$0, and should be skewed toward small location errors. For this reason, we expressed confidence levels for estimated locations as the distances that contained 90 and 95% of the Es (i.e., 90 and 95% quantiles).

We converted the linear measure of location

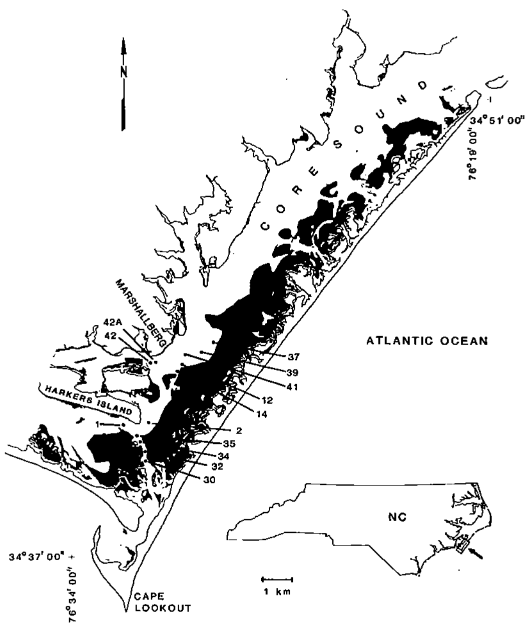

Fig. 1. Submerged aquatic vegetation (shaded areas) and location of channel markers and beacons in Core Sound, North Carolina (1:170,000). Map adapted from Ferguson et al. (1993).

precision to an areal measure (A_e), using the confidence distance (i.e., specified quantiles) as the radius of a circle around the estimated point location (Zimmerman 1992). Location error also was expressed in terms of D_g. This is a single measure of distance that related the distances from 2 receivers (x_1, y_1 and x_2, y_2) to the estimated location (x, y) (Hupp and Ratti 1983), and for any angle of intersection, it is estimated as $\sqrt{d_1 \cdot d_2}$ where $d_1 = \sqrt{(x-x_1)^2 + (y-y_1)^2}$ and $d_2 = \sqrt{(x-x_2)^2 + (y-y_2)^2}$ (Zimmerman 1990). We used D_g to assess precision of E_r at selected distance intervals. We examined differences in E_r at selected distance intervals, using a random effects ANOVA after a square root transformation to meet normality assumptions. We also compared areal measures of specified statistical confidence (i.e., A_e90, A_e95) with the frequency distribution of habitat polygon sizes in southern Core Sound. We obtained sizes of habitat polygons from Ferguson et al. (1992).

We evaluated the suitability of LORAN and DGPS to determine monitoring platform location. To evaluate LORAN, we calculated standard errors of 40 geocoordinates obtained during each of 5 data collection sessions at a U.S. Geological Survey horizontal control station located near southern Core Sound. We used a LORAN (Model II Morrow Apollo 800 Flybuddy) to estimate location of the monitoring platform using the World Geodetic System (WGS-84) coordinate system. We calibrated LORAN at the control station immediately before data collection began by manipulating time delays such that the initial instrument reading made up the known geocoordinates of the position. To evaluate DGPS, we took 40 readings during 10 minutes, at each of 5 surveyed markers and beacons. We differentially corrected DGPS field station location coordinates to improve accuracy of the position estimate, using a nearby reference site (20 km) located at the National Marine Fisheries Service Beaufort Laboratory, North Carolina. We compared positions obtained from LORAN and DGPS with known locations. We calculated horizontal errors for each geoposition obtained during each of 5 data collection sessions, averaged over 10 minutes. We averaged north and east coordinates within a data collection session and calculated the deviation of the averaged session from the known location. We compared location errors calculated using coordinates of known locations with those from DGPS using a t-test after a square root data transformation.

RESULTS

Of 13 markers and beacons selected for system evaluation, only 6 were usable to estimate angle errors. Reduction in number was because signals could not be detected beyond 1.2 km despite their potential range of 3 km. Also, background noise near Harkers Island interfered with signal reception. This reduction limited the station combinations from which we obtained location estimates, particularly at close range.

Except for angle errors associated with station combination 42 to 42A, errors differed from zero (Table 1). Angle errors associated with channel marker 39 were large. This error was consistent between observers (t = 0.61, 28 df, P = 0.54). Although precision (SD = 3.84) was lower than at 2 other test-site locations, errors were outside the range of other data (Fig. 2). For this reason, we excluded these data from the angle error assessment data pool, but data were later used for location estimation after correcting for bias (White and Garrott 1990). After excluding marker 39, angle errors ranged from −17 to 12° (Fig. 2). Angle errors varied among stations (F = 11.94; 3, 166 df; P < 0.001), with the largest

Table 1. Angle errors (in degrees) obtained from 5 transmitting (T)-receiving (R) stations to evaluate bias and precision using sonic telemetry in June 1991, Core Sound, North Carolina (n = 30/combination).

Station combination T to R	Distance[a] (m)	True bearing	Angle error: Bias ($\bar{e}$)	Angle error: Precision (SD)	Angle error: Range
42 to 42A	167	92°	1.8°	2.88	−5 to 8°
41 to 42	1,256	76°	−3.2°[b]	6.78	−10 to 12°
41 to 14	406	20°	−5.8°[b]	5.62	−17 to 7°
41 to 12	927	22°	−2.8°[b]	3.31	−9 to 6°
41 to 39	774	264°	−25.9°[b]	3.84	−36 to −21°
Overall[c]			−2.5°	5.67	−17 to 12°

[a] Distance between stations.
[b] Means were different from zero (t-tests, P < 0.001).
[c] Excluding bearings from marker 39, which were considered outliers (adjusted to n = 120).

bias associated with station combination 41 to 14.

We obtained 45 estimated locations and D_g from 3 pairs of receiving stations whose angles of intersection were 96, 116, and 117° (Table 2). Location errors varied with geometric distance (F = 4.71; 2, 42 df; P = 0.01), exhibiting an increasing pattern with D_g (Table 3). The 90 and 95% confidence areas for pooled data were 11.10 and 21.20 ha, respectively. The smallest confidence areas were associated with the smallest D_g interval: A_e90 = 2.16 ha and A_e95 = 2.84 ha (Table 3). Seagrass beds in Core Sound have a contiguous distribution and their size distribution is skewed toward small beds (median = 1.5 ha, range 0.07–3,189 ha, n = 177). Areal confidence measures about all E_m were greater than the median size of seagrass habitat polygons in southern Core Sound (Ferguson et al. 1992).

Precision of LORAN was poor because the range of geopositions obtained from this system was large (Table 4). During a single data collection session the standard error of the means ranged from 4 to 9 m. Averaged session positions ranged from 54 to 70 m from the known location. In contrast, DGPS estimates of averaged position ranged from 2 to 4 m from the known location. Standard errors of the DGPS means were small (<0.5 m). The average difference between location errors calculated using coordinates from known locations (i.e., NCGS) and those obtained from DGPS was 0.56 with a 95% confidence interval of ±1.29 m (n = 45). Location errors (E) obtained from both sets of coordinates were not different (t = 0.08, 88 df, P = 0.94).

Table 2. Median location error (E_m) (95% quantile), mean geometric distance (D_g) (±SD), and ranges in meters for each transmitting (T) and pair of receiving (R-R) station combinations obtained using sonic telemetry in June 1991, Core Sound, North Carolina (n = 15/combination).

Source[a] T to R-R	Location error: E_m (95% quantile) Range	Geometric distance: D_g (SD) Range
41 to 39-14	59.1 (123.6)	555.0 (33.9)
	14.6–132.0	514.5–637.2
41 to 39-12	68.8 (187.0)	839.4 (32.4)
	16.5–187.9	779.3–898.3
41 to 12-42	131.8 (279.9)	1,093.6 (146.5)
	23.1–281.0	839.1–1,330.0
Overall (n = 45)	75.6 (259.6)	829.3 (238.8)
	14.6–281.0	514.5–1,330.0

[a] Station no. refer to site locations in Fig. 1.

DISCUSSION

Power of statistical tests for use of habitat studies depends on system accuracy (White and Garrott 1986, Nams 1989, White and Garrott 1990). Similarly, measures of location error and precision define the magnitude of movement that can be measured with confidence for a given set of receiving stations (Laundre et al. 1987). Angle errors varied among stations, but the magnitude of the bias for the farthest stations

Table 3. Median location error (E_m) and associated confidence areas (A_e) at 90 and 95% level for selected geometric mean distance (D_g) intervals and all data irrespective of D_g obtained using sonic telemetry in June 1991, Core Sound, North Carolina. Points outside the selected intervals were excluded from calculations.

D_g (m)	n	E_m (m)	A_e90 (ha)	A_e95 (ha)
500–600	14	58.4	2.16	2.84
800–900	14	64.7	3.74	6.11
>900–1,200	10	102.4	7.76	8.26
Overall	45	75.6	11.10	21.20

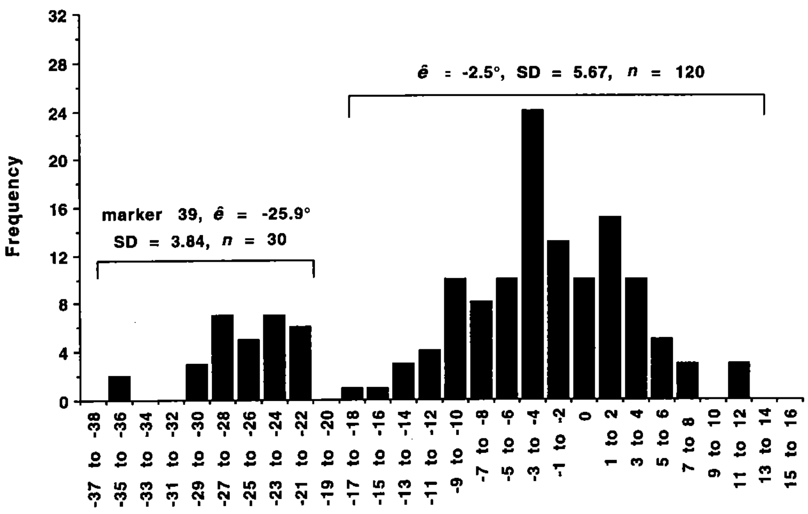

Fig. 2. Angle error (ê) distribution generated from 5 transmitting-receiving station combinations using sonic telemetry in June 1991, Core Sound, North Carolina. Errors from marker 39 did not overlap with any obtained from other stations and were excluded from angle error assessment.

was not the largest. Similar findings have been reported by Springer (1979) and Zimmerman (1992). They suggested that, with increasing distance, signal reception occurs within a narrower arc and precision is usually maintained or improved. Precision problems at closer range may have been due, in part, to difficulties in selecting the loudest signal bearing within a broad arc (Zimmerman 1992).

We are uncertain about what caused the bias associated with marker 39. Interobserver variability did not contribute to the bias. Water depth, a factor known to affect signal transmission (Winter 1983), averaged 2.8 m (range 2.5–2.9) between transmitting-receiving stations.

Table 4. Mean horizontal errors ± SE and deviation from the known location (i.e., marker) in meters associated with geopositions obtained from Differential Global Positioning (DGPS) and Long Range Navigation (LORAN) systems in June 1991, Core Sound, North Carolina. Data were collected during 5 sampling sessions (n = 8/session).

	DGPS			LORAN		
Marker[a]	$\bar{x}$ error	SE	Session deviation	$\bar{x}$ error	SE	Session deviation
14	4.91	0.49	2.27	98.86	9.20	62.36
12	3.72	0.24	3.10	89.82	8.68	63.43
42A	2.98	0.19	2.28	89.22	8.50	60.93
42	4.52	0.30	3.94	72.71	4.57	69.96
39	5.62	0.46	3.13	63.60	3.98	54.35

[a] Channel marker surveyed by N.C. Geodetic Surv.

Thus, we believe that it did not play a major role in causing bias. Signal deflection by submerged spoil deposits, common in the area, was discarded as an explanation because none occurred between markers 39 and 41. Other factors that might affect signal reception include temperature profiles, suspended particulate matter, and vegetation (Brumbaugh 1980, Winter 1983, Lagardere et al. 1990). These possibilities emphasize the need for adequate system tests conducted across the range of conditions, temporal and physical, thought to be encountered during a study.

Location estimates reported herein were obtained from receiving stations whose angle of intersection fell within 45 and 135°, the recommended range for telemetric studies (Springer 1979). Our findings were consistent with radio telemetry studies in that location errors increased with geometric distance (Zimmerman 1992). Accordingly, within the range of distances evaluated in this study, areal measures of confidence at D_g 0.5–0.6 km minimize the probability of misclassifying use of habitat (Nams 1989) and set the finest level of resolution at which use of habitat patterns and movement can be described.

Habitats in Core Sound are classified as vegetated and nonvegetated types, where seagrasses cover about 35% of the subtidal land in southern Core Sound (Ferguson et al. 1993). Mapping of submerged vegetation was achieved with aerial photogrammetry, and the smallest mapping unit = 0.01 ha. To the east, Core Sound substrate consisted of almost continuous beds of aquatic vegetation and areas of discontinuous seagrass cover, whereas along the mainland, substrate consisted of isolated, long strips of continuous and patch habitats (Fig. 1). Size distribution of habitat polygons is skewed toward small beds (median = 1.5 ha) and most are smaller than the A_e90 = 2.16 ha for D_g 0.5–0.6 km, limiting our ability to test for use of habitat. Location estimate improvements, coupled with suggestions to increase test efficiency (Nams 1989), are necessary before strong inferences about use of habitat are possible. Attained levels of accuracy and precision, however, might be useful in some areas and circumstances. For instance, small polygons ($\leq$1.5 ha), although comprising 56% of the beds (n = 117), represented <0.6% of the total seagrass coverage. Ninety-seven percent of the seagrass coverage was associated with beds larger than A_e95 = 8.26 ha for D_g >0.9–1.2 km, providing some opportunities for habitat studies. We also believe that it is possible to determine the coincidence of sea turtles (i.e., time and space) and various fisheries in selected areas of Core Sound. The emphasis of this work would be on distribution and movement, both fairly independent of polygon size constraints, not on the underlying resources determining distribution, which would require greater accuracy.

Our results underscore the need to guard against spurious location estimates that may be caused by deflected signals (those associated with 20% of our test locations [marker 39]). White and Garrott (1990) recommended increasing the number of receiving stations to ensure that $\geq$3 bearings are obtained for accurate location estimates when working with free-ranging, instrumented animals. In sea turtle studies, logistical constraints (e.g., no. of boats) may preclude this option, in which case, increased test efficiency (Nams 1989) becomes that much more critical. Receivers should be equipped with a built-in signal intensity resolution feature. Such a feature doubles the information available to the observer, aiding in selection of the bearing associated with the strongest signal (J. Braun and S. P. Epperly, NMFS, Beaufort, N.C., unpubl. data). Lowering the signal wavelength frequency of transmitters (e.g., $\leq$50 kHz) may aid in bearing selection as well because it increases the range at which signals can be detected. Finally, it is also possible to improve location estimates by decreasing the distance between receivers and the instrumented animal. J. Braun and S. P. Epperly (unpubl. data) found that A_e95 was as low as 0.3 ha in grassbed areas in Core Sound for a D_g ranging from 43.5 to 84.6 m. However, precision was not better in a different channel area (A_e95 = 6.8 ha), a habitat similar to where our evaluation took place, even though D_g was smaller (188.9–275.3 m) than in this study.

In sea turtle use of habitat studies, mobile stations (e.g., boats) might be necessary to achieve monitoring flexibility. Consequently, proper evaluations must be performed prior to adopting a positioning system. Precision of position estimates of a stationary boat anchored at a known location (i.e., channel marker) were poor, averaging 62 m, when obtained from LORAN. In contrast, positions obtained from DGPS varied by 3 m. Differences are probably due to factors influencing location estimates and our ability to correct for errors. In GPS, all factors affecting accuracy and precision can be computed, except the effects of solar radiation pressure on the satellite's orbit and tropospheric delay of the signals (Leick 1990). Accurate clocks and satellite ephemeris information are the core of the GPS system. Global Positioning System satellites transmit signals from which the distance between satellite and receiver can be calculated. Error corrections can be extracted from these signals and from carrier phase information, an indication of delay caused by the ionosphere. Differential correction of field data (DGPS), the comparison of a known position with the position determined by GPS at the same time and location, and the application of the difference to field data, increases accuracy to <5 m (Leick 1990). LORAN accuracy is influenced by the angle of intersection between 2 hyperbolic lines of position calculated from the time differences between signals transmitted from 3 fixed towers, by the spacing between 2 adjacent lines of position, and by terrain, mineral deposits, temperature, moisture content, and electrical fields that affect the speed of radio waves (Maloney 1978). Most of these factors vary within a site over time, and all vary geographically.

Location estimates derived from DGPS were not different from those obtained from coordinates of known locations (i.e., NCGS). Therefore, DGPS did not represent another source of error affecting location estimation, and portable

GPS units, coupled with differential correction of the field data, provide study design flexibility. Global Positioning System units must have an unrestricted view of the sky. The usefulness of LORAN versus DGPS must, of course, be determined by goals of the study. The DGPS should be adopted if determining use of habitat is an essential component of the study. The DGPS is inherently more accurate than LORAN and is unaffected by geography because access to satellite signals is physically unrestricted in coastal environments. Otherwise a network of fixed receiving stations is needed to ensure accurate position estimates. Optimal number and location of stations can be determined following recommendations by White (1985) and White and Garrott (1990).

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